Pleistocene and early Holocene palaeo-landscapes of the Dogger Bank South Wind Farm Sites

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ABSTRACT

A preliminary ground model was prepared for the planned Dogger Bank South Wind Farm Sites in the UK sector of the North Sea. This ground model is based on a geological interpretation of 2D Ultra Ultra High Resolution Seismic (UUHRS) data and geotechnical data. The interpretation results include seismostratigraphic horizons which delineate major soil units. Mapping of these soil units is important for the planning and design of wind turbine locations and inter array cables. Additionally, these horizons reveal (1) multiple generations of buried palaeochannels and (2) evidence for shifting coastlines.

The buried palaeochannels have tributaries and contain evidence for the local presence of marshlands (peat beds) beyond the channel margins. These landscapes formed during the Pleistocene and were subsequently flooded when sea level rose as a result of meltwater release from rapidly decaying ice sheets. Locally, thick sequences of early Holocene marine sand deposits show evidence of large-scale clinoforms, which indicate that palaeocoastlines prograded seaward over a distance of up to 20 km during the early Holocene. The top of these clinoforms contain erosion surfaces and gravel lags, indicating sub-aerial exposure of the delta top. This shows that while in general ‘Doggerland’ was rapidly flooded during the early Holocene, there were short periods when the land area expanded.

Keywords: ground model; offshore wind; Doggerland, Botney Cut Formation, Swarte Bank Formation

1. Introduction

The Dogger Bank is a shallow area in the southern North Sea with the shallowest depth of 13 m below LAT (Lowest Astronomical Tide), while the surrounding seafloor is 50 m to 75 m below sea level (Fig. 1). The Dogger Bank formed during the last glacial period (Weichselian) as a complex push-moraine (Cotterill, et al., 2017; Phillips et al., 2018, 2022; Roberts et al., 2018) under both spatially and temporally rapidly changing depositional environments due to ice-marginal dynamics (Emery et al., 2019a, 2019b, 2020).

Most available high resolution data from the Dogger Bank are from the central part of the Dogger Bank in the British Sector, acquired as part of offshore wind surveys in the early 2010’s. However, less data are available from the margins of the Dogger Bank. Here we present the interpretation results of 2D ultra ultra high resolution (2D-UUHR) multichannel seismic data and geotechnical data acquired for the large (1000 km2) Dogger Bank South Wind Farm Sites, located at the south-western margin of the Dogger Bank where it transitions in the Outer Silver Pit (Fig. 1).

The results of this site investigation are used for the site selection and lay-out design of offshore wind farms, but also give insight in the geological history of the site. This is of interest for reconstructing the landscapes and relative sea level rise of areas inhabited by humans, and may also provide context for future landscape changes and sea level rise in formerly glaciated areas.

2. Geological Setting

The North Sea basin is a failed Mesozoic rift and contains a thick succession of Cenozoic sediments deposited during post-rift thermal subsidence (McKenzie, 1978). During the Eocene, marine clays were deposited (BGS, 1985). These Eocene marine sediments are overlain by Early to Middle Pleistocene marine and fluvial sands of the Markhams’s Hole and Yarmouth

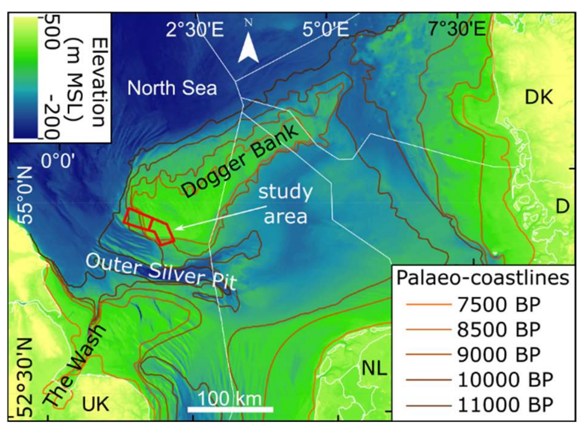

Figure 1. Digital elevation map relative to Mean Sea Level (colour scale stretched; GEBCO Compilation Group, 2023) of the southern North Sea including the Dogger Bank, the Dogger Bank South Offshore Wind Farm Sites, and the ages of palaeocoastlines (after Påsse and Andersson, 2005; Christensen and Nielsen, 2008; Sturt et al., 2013; Özmaral et al., 2022).

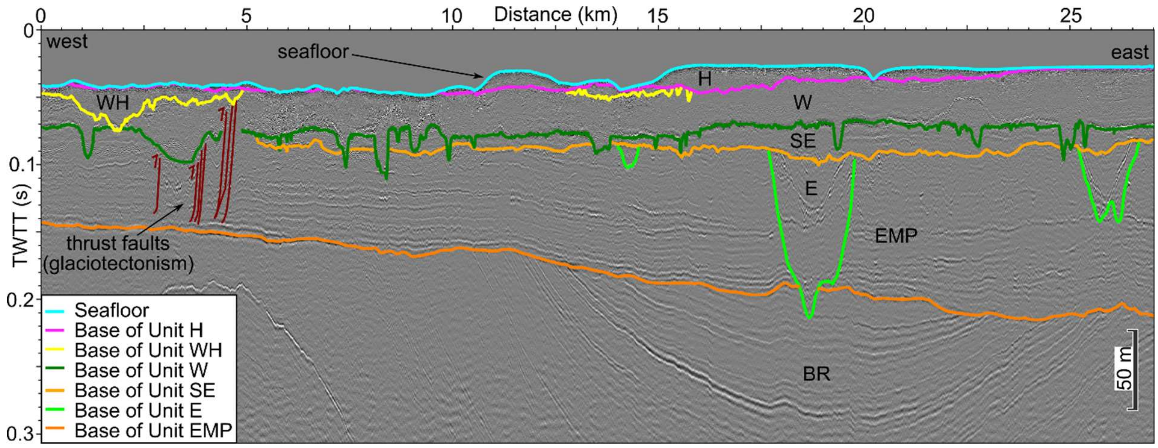

Figure 2. Overview of the seismostratigraphic units.

Roads formations which were deposited by prograding river deltas (BGS, 1986; Overeem et al., 2001; Gibbard & Lewin, 2016).

During the Middle to Late Pleistocene, the study area was covered by ice during the Elsterian glacial period when tunnel valley fills of the Swarte Bank Formation formed (BGS, 1986). During the Saalian glacial period the study area may also have been covered by ice, but any evidence of this may have subsequently been eroded. A marine environment covered the study area during the Holsteinian and Eemian interglacial periods (BGS, 1986). During the last glacial period (Weichselian), the Dogger Bank formed as a push-moraine as results of a complex interaction between variable glacial and periglacial depositional environments and ice sheet advances and readvances (Cotterill, et al., 2017; Phillips et al., 2018, 2022; Emery et al., 2019b, 2020). During the early Holocene, after a period of subaerial exposure, the study area was flooded due to the melting of decaying ice sheets (Sturt et al., 2013; Emery et al., 2019a).

The complex stratigraphy of the Dogger Bank demonstrates the complex and dynamic evolution of depositional environments across the study area.

3. Data sets

2D ultra ultra high resolution (2D-UUHR) seismic reflection data were acquired with 15,000 line kilometres and 100 m line spacing. The seismic data were acquired using a Fugro Multi-Level Stacked Sparker (360 tips) and a Geometrics GeoEel LH16 96 channel hydrophone streamer with a maximum penetration depth of 200 m to 250 m LAT.

Geotechnical data were acquired at 14 locations. Seabed CPT's were acquired at 12 locations with final depths ranging from 17 m to 43 m BSF. Boreholes with downhole sampling and downhole CPT's with a target depth of 55 m BSF were performed at 5 locations. Therefore, at 3 locations a combination of a seabed CPT and downhole data were acquired.

4. Results

4.1. Overview

Fig. 2 and Table 1 provide an overview of the main seismostratigraphic units. Seven major seismostratigraphic units are present in the study area. Sections 4.2 to 4.8 describe the units in more detail.

4.2. Unit BR

The deepest unit recognized in the study area is acoustically stratified and folded. Based on literature, this unit comprises Eocene marine clay (BGS, 1985).

4.3. Unit EMP

Unit EMP is a horizontally stratified unit which unconformably overlays Unit BR. This unit gradually increases in thickness from 40 m in the west to 200 m in the east. Towards the top, this unit gradually contains more internal erosion surfaces. This unit was sampled by boreholes at only 2 locations. It comprises very dense fine to medium sand, locally with laminations of clay or organic material. In the top 5 m, this unit comprises clay or a mix of sand and clay, however the lateral extent of the clay is uncertain.

It is interpreted that these deposits are marine sands of the Markham's Hole Formation and/or fluvial sands of the Yarmouth Roads Formation. These units are Early to Middle Pleistocene in age (BGS, 1986). The clay in the top of the unit may be the result of variable depositional environments in the delta top, such as abandoned channels and overbank deposits.

4.4. Unit E

Channels of Unit E incise in Unit EMP (Fig. 3d,e). The channel incisions are up to 3 km wide, reach a maximum depth of 233 m below LAT and have a meandering planform (Fig. 4). Locally, channels of Unit E erode down in the top of Unit BR. Internally, the base of these channels is acoustically chaotic. Towards

Table 1. Overview of seismostratigraphic units.

Unit	Seismic Character	Soil Type	Depositional Environment	Age	Formation
H	Acoustically transparent, contains clinoforms, and the top contains erosion surfaces and is acoustically chaotic.	Sand with shells and shell fragments, locally gravelly.	Marine	Holocene	Holocene
WH	Acoustically transparent, stratified and complex.	Sand with shells and shell fragments and/or sandy clay.	Fluvial to marine	Late Weichselian to Early Holocene	Botney Cut?
W	Acoustically chaotic and complex, including folding and thrust faults.	Brown sandy and gravelly clay; grey sandy clay with organic matter and beds of sand.	Subglacial till and/or glacio-lacustrine; deformed	Weichselian	Bolders Bank and/or Dogger Bank
SE	Acoustically transparent to stratified.	Sand which is locally gravelly, silty and contains organic matter; sand with shells and shell fragments; locally, the sand is interbedded with clay.	Fluvial to marine	Holsteinian? Saalian and/or Eemian	Egmond Grounds, Kettle Hole, Cleaver Bank and/or Eem
E	Acoustically chaotic at the base, becoming well stratified towards the top.	Poorly sorted clayey gravelly sand interbedded with sandy clay; well sorted coarsening upward successions.	Tunnel valley fill	Elsterian	Swarte Bank
EMP	Stratified, gradually includes more internal channeling towards the top.	Sand with laminations of clay and organic matter; with clay in the top of the unit.	Fluvio-deltaic	Early to Middle Pleistocene	Yarmouth Roads and/or Markham's Hole
BR	Stratified and folded.	Clay.	Marine	Eocene	Nordland/ Hordaland Gp.

the top of this unit, the seismic character is often well stratified. This unit was sampled by boreholes at only 2 locations. Where the seismic character is chaotic, the soil type comprises dense to very dense, grey fine to medium clayey and gravelly sand interbedded with very high strength sandy clay (150 kPa to 400 kPa undrained shear strength). Where the seismic character is well stratified, the soil type coarsens upward from very high strength grey clay to very dense brown fine to medium sand with shells and shell fragments.

It is interpreted that Unit E represents the fills (Swarte Bank Formation) of tunnel valleys formed during the Elsterian (BGS, 1986). The acoustically chaotic base with comprising poorly sorted soils is interpreted to be deposited in sub-glacial environments. The stratified upper part with coarsening-upward graded soils containing shells and shell fragments is interpreted to be deposited in marine environments during the Holsteinian interglacial period which followed the Elsterian glacial period.

4.5. Unit SE

Unit SE unconformably overlays older units. This unit is the infill of a shallow (<10 m thick) but wide (20 km) valley with steep margins (Fig. 3g), giving an overall planar geometry (Fig. 4). Internally, this unit is acoustically stratified to acoustically transparent. This unit was sampled at only 4 geotechnical locations. It comprises dense brown fine to medium sand with shells and shell fragments and dense to very dense grey fine to medium sand which is locally gravelly, silty and contains organic matter. The sand is interbedded with very high strength grey clay.

It is interpreted that the erosional base forming the wide valley was formed by fluvial processes during a glacial period when the North Sea Basin was dry land. The funnel-shaped valley may have an estuarine origin (Dalrymple et al., 2012) formed when the North Sea was flooded after a glacial period. The silty and gravelly sand with organic matter may be associated with this fluvial phase. The acoustically stratified and transparent character and interbedded clay point toward a low energy marine environment. The presence of sand with shells and shell fragments is also an indicator for a marine environment. Therefore, it is interpreted that the valley which forms the base of this unit formed during a glacial period by fluvial processes, and that the valley was filled in a marine depositional environment in the subsequent interglacial period. Since Unit E is Elsterian in age and Unit W is Weichselian in age, this would mean a Saalian (glacial) to Eemian (interglacial) age of Unit SE. It is deduced that the age must be late Saalian, because early Saalian deposits would likely have been eroded during the main Saalian ice sheet advance.

This unit may correspond to the Tea Kettle Hole, Cleaver Bank and/or Eem Formations. It may also correspond to the Egmond Grounds Formation if this unit would be considered to be Holsteinian in age (BGS, 1986).

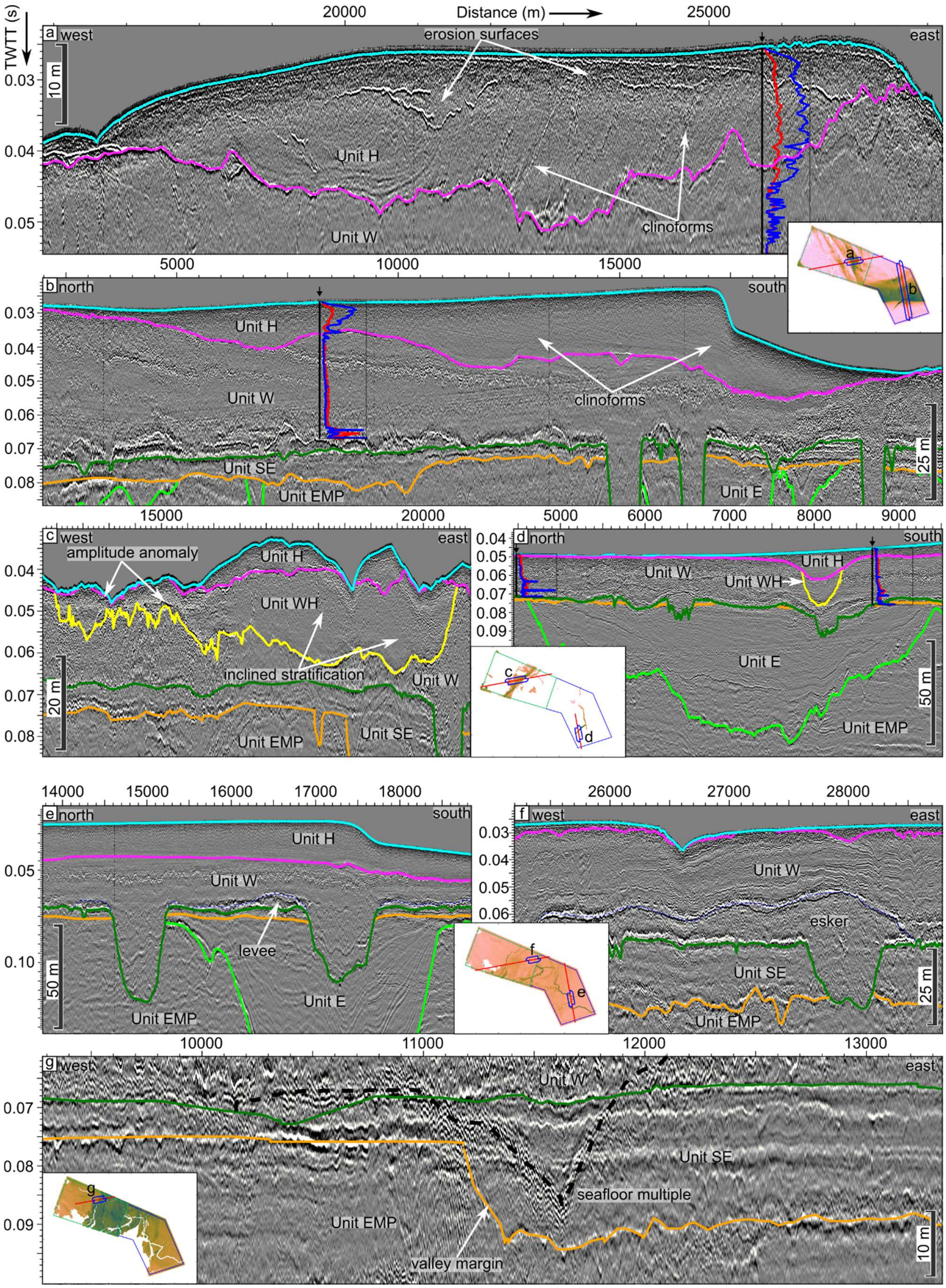

Figure 3. Data examples of a) and b) Unit H, c) Channel of Unit WH, d) Valley of Unit WH, e and f) Channels at the base of Unit W, g) Valley margin of Unit SE. The geotechnical locations show cone resistance in blue with a scale of 0 to 50 MPa and sleeve friction in red with a scale of 0 to 1.25 MPa.

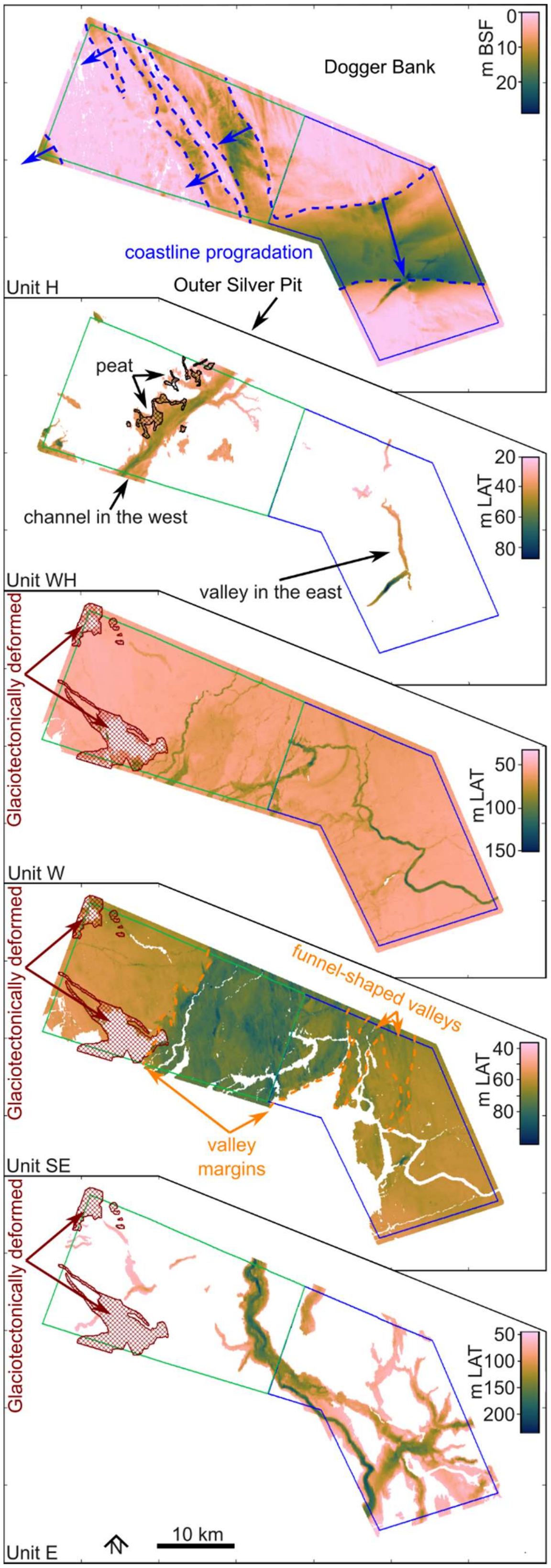

Figure 4. Maps of the bases of the seismostratigraphic units. All maps are in depth below LAT, except for Unit H which is in BSF (below seafloor).

4.6. Unit W

Unit W unconformably overlays Unit SE and is locally exposed at or close to the seafloor. This unit has a planar geometry and has a thickness of 10 m to 40 m. Locally, the base of Unit W is formed by channels with a width of 250 m to 1000 m where Unit W reaches a maximum thickness of about 130 m. The channels have a meandering planform (Fig. 4). An asymmetric positive relief is often present on either side of the channels with the steep side in the direction of the channel (Fig. 3e). Locally, a positive relief is present above the channels (Fig. 3f). Internally, this unit is acoustically stratified (Fig. 3f), chaotic or complex and includes internal reflectors (Fig. 3b), folded strata and thrust faults. In the west of the study area, the thrust faults locally detach at a deeper level (Fig. 2, 4).

This unit was sampled at 10 geotechnical locations. It comprises brown sandy, gravelly clay and sandy grey clay with organic matter. The gravel is polymict including chalk and basalt. Horizontally to vertically orientated fissures have been observed in the clay samples. The clays have an undrained shear strength ranging from 50 kPa to 350 kPa and are interbedded with very dense sand and locally gravelly sand.

Based on the meandering planform and their stratigraphic position, it is interpreted that the channels at the base of Unit W were formed by rivers flowing through the study area when the North Sea was dry land during the early stages of the Weichselian glacial period when the ice sheet did not yet reach the study area. The positive relief bordering the channels is interpreted to be levees, supporting the interpretation of sub-aerial (rather than sub-glacial) deposition. Some channels cross-cut each other and have a positive relief above the channel. This indicates that some channels were eroded during a later stage relative to other channels. The positive relief may be an esker, associated with sub-glacial water flow, which may have exploited the existing channels once the area was covered by ice.

Based on the poor sorting of the brown clays, it is interpreted that this unit was partially deposited as subglacial till. The continuous internal reflectors may represent the boundary between till sub-units (Fig. 3b) or lenses and beds of coarse material. The stratified seismic character and grey clays with organic matter may indicate deposition in a proglacial lacustrine environment. The interbedded sand may have a glaciofluvial origin or deposited in nearshore lacustrine environments (Emery, 2019b, 2020).

Unit W correlates with the Dogger Bank Formation in the centre of the Dogger Bank (BGS, 1986). However, brown poorly sorted clay is traditionally assigned to the Bolders Bank Formation which is present to the south-west of the Outer Silver Pit (Fig. 1; BGS, 1986). The interbedding of these two types of clay may be the result of spatially variable interaction between ice sheets (Phillips et al., 2022). The deformed grey clays and sands on the Dogger Bank are the result of deposition in pro-glacial lacustrine and peri-glacial environments and subsequent deformation during ice sheet advances. This process can be repeated multiple times due to ice-marginal dynamics, resulting in a complex stratigraphic architecture (Cotterill et al., 2017; Phillips et al., 2018, 2022; van Cappelle et al., 2023). The brown glacial tills assigned to the Bolders Bank Formation were deposited during the furthest advance of the British-Irish ice sheet into the Outer Silver Pit and surrounding areas (Roberts et al., 2018). Since the study area is located in the transition area between the Dogger Bank and Outer Silver Pit (Fig. 1), it is interpreted that Unit W is the result of a complex interaction between depositional environments and ice-marginal dynamics of 1) the ice sheet advancing from the central North Sea which build the Dogger Bank push-moraine and 2) the ice sheet which advances through the Outer Silver Pit during the furthest advance during the last glacial period (Roberts et al., 2018; Phillips et al., 2022).

4.7. Unit WH

Unit WH is a locally present channelised unit which overlies and incises Unit W and is locally exposed at or close to the seafloor. Two main infilled channels are present, one in the west and one in the east (Fig. 4).

The channel in the east is orientated north to south to north-east to south-west, and is relatively narrow (750 m) and reaches a relatively high maximum depth of about 90 m below LAT. The channel infill is stratified (Fig. 3d). The stratification is curved parallel to the base of the channels. Above this channel, Unit H also thickens. This channel was sampled by only 1 borehole, where it showed fine to medium sand with shells and shell fragments and organic matter and a bed of clay.

The channel in the west is orientated north-east to south-west, and is relatively wide (5 km) and shallow (approximately 60 m LAT). In cross-section, the channel is asymmetric with the deep part in the east (Fig. 3c). In planform, this channel has small tributary channels (Fig. 4). The infill in the deep part of the channel is acoustically transparent to stratified. The stratification is inclined. In the shallow part of the channel in the west, the seismic character is more complex and includes high amplitude seismic anomalies with a negative polarity. These anomalies can be correlated over distances of hundreds of metres. This channel is sampled by only 1 borehole and comprises sandy clay (20 kPa to 30 kPa undrained shear strength) with organic matter. Since channel fills are usually variable, the 2 geotechnical locations are unlikely to be representative for the entire unit.

The relatively narrow and deep channel in the east has the geometry of a tunnel valley and is therefore interpreted to have been eroded when the ice sheet covered the study area. These deposits are traditionally assigned to the Botney Cut Formation (BGS, 1986). Based on the presence of shells and shell fragments, at least part of the tunnel valley infill was deposited when the valley was flooded by a marine environment during the earliest Holocene.

The channel in the west has tributary channels. The seismic anomalies which are present in the shallow part of the channel are interpreted to be peat beds deposited in a wetland environment (Keizer et al., 2014). The inclined bedding in the channel fill may indicate deposition on point bars. Therefore, it is interpreted that this channel was part of a sub-aerial network draining the Dogger Bank at the end of the last glacial period (Gaffney et al., 2009; Cotterill et al., 2017; Emery et al., 2019b, 2020).

4.8. Unit H

Unit H overlies Unit W and Unit WH. In the north, west and south of the study area, this unit is absent or thin (up to 3 m thick). Particularly in the east, but also in the west of the study area, this unit thickens into wedges of up to 25 m thick (Fig. 4). These wedges are located at the transition from the shallow water depth at the Dogger Bank to deeper water to the south-west. They are up to 20 km wide. Internally, these wedges contain clinoforms dipping towards the south and west (Fig. 3a,b). The top of this unit has a more complex seismic character and contains internal erosion surfaces incising in older deposits and point reflectors (Fig. 3a). This unit was sampled by all geotechnical locations and comprises loose to very dense fine to medium sand with shells and shell fragments and is locally gravelly.

The clinoforms associated with the increased thickness at the margin of the Dogger Bank are interpreted to be the result of coastline progradation during the early Holocene (Helland-Hansen & Hampson, 2009). The presence of shells and shell fragments are an indication for a marine depositional environment. The presence of gravel associated with incising erosion surfaces at the top of this unit is interpreted to be deposited by braided river systems in a coastal plain feeding the coastlines at the top of the clinoforms. The top of this unit is interpreted to be susceptible to reworking in the present marine environment (Riera et al., 2023).

5. Discussion

5.1. Channel networks

Buried palaeochannels and valleys of various origins are present at four levels: The tunnel valleys of Unit E, the wide valley of Unit SE, the channels at the base of Unit W and the channels and valleys of Unit WH. The origins of the tunnel valleys of Unit E and Unit WH are related to ice marginal processes during the Elsterian and Weichselian respectively (Fig. 5c; Cotterill et al., 2017; Laban & van der Meer, 2022).

The channels and valleys with a fluvial origin give an insight in the landscape in which humans lived. These channels and valleys can be grouped in two categories. Firstly, Unit SE is up to 15 km wide and covers a large proportion of the study area. Based on the scale of the valley, this must have been a major valley draining the southern North Sea Basin when it was dry land during the latest stage of the Saalian glacial period when the ice sheet was already retreating. As such it was part of the 'Rhine-Thames landscape' (Fig. 5b). During the Saalian, the Thames already flowed southward through the Dover Strait to the Channel, however the courses of the Rhine and Meuse shifted at some point between the late Saalian and early Weichselian glacial periods from northward courses into the North Sea to southward courses through the Channel (Gupta et al., 2007; Peeters et al., 2015; Hijma et al., 2011). After the Elsterian glaciation, rivers in the Midlands and Northern England drained towards the north-east through what is now The Wash (Belshaw et al., 2014). The wide valley of Unit SE may be a trunk river downstream of confluences of several of these rivers.

The second category includes the relatively narrow channels at the base of Unit W and Unit WH. These channel networks formed during the Weichselian glacial period when the North Sea was dry land respectively before and after the ice sheet covered the study area. Based on relatively narrow and shallow channels, and meandering planform, these must have been local channel networks draining the Dogger Bank area (Fig. 5a; Gaffney et al., 2009; Cotterill et al., 2017; Emery et al., 2020; EMODnet, 2023). The presence of seismic anomalies in Unit WH are interpreted to be peat beds which indicate that wetlands were present along river systems during the late Weichselian to early Holocene (Keizer et al., 2014).

5.2. Early Holocene coastline progradation

After the last glacial maximum, sea levels rose quickly. Within 4000 years from the onset of the Holocene, the Dogger Bank was completely flooded (Sturt et al., 2013). However, Unit H shows evidence for four phases of seaward coastline progradations of up to 20 km in the form of clinoforms (Helland-Hansen & Hampson, 2009). The position of the palaeocoastline was over the study area, between approximately 10,000 and 8,500 years BP (Sturt et al., 2013). This shows that there were brief episodes of coastline progradation during the overall drowning of Doggerland (Fig. 1, Fig. 5a; Sturt et al., 2013; Emery et al., 2019a).

6. Conclusions

A preliminary ground model was prepared for the planned Dogger Bank South Wind Farm Sites in the UK sector of the North Sea. This ground model is based on a geological interpretation of 2D UUHR seismic data aligned with geotechnical data at 14 locations. The interpretation results include 7 major soil units. The acquired data are primarily used for the site selection and lay-out design of offshore wind farms. In general, the results of this preliminary ground model are in line with existing understanding of the Dogger Bank. However, the valley at the base of Unit SE was not recognized before. Also, due to the location of this study area at the south-west margin of the Dogger Bank, part of Unit W has characteristics more like glacial tills of the Bolders Bank Formation than the Dogger Bank Formation elsewhere on the Dogger Bank. Likewise, the thick sand wedges of Unit H with clinoforms at the margin of the Dogger Bank are present in the study area, but not on the central part of the Dogger Bank.

The presented data give insight in the evolution of the landscapes in which humans lived. These landscapes include buried palaeochannel networks at 4 different

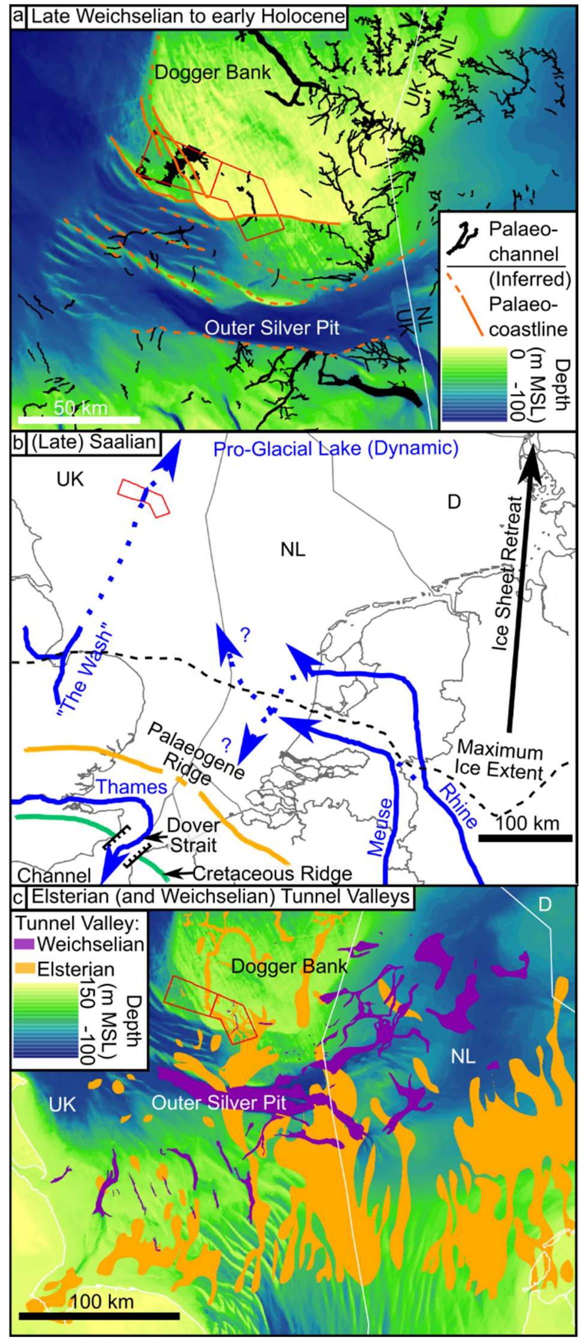

Figure 5. Palaeogeographic reconstructions, see discussion for references. Colour scales are stretched. A) Late Weichselian channel systems and early Holocene coastline positions. B) Late Saalian drainage networks, c) Tunnel valleys.

levels representing palaeo-landscapes at 4 periods in time, including glacial valleys, a large fluvial trunk valley during the Saalian glacial period and two local drainage networks during the Weichselian glacial period. The latter includes wetlands along the river during the late Weichselian to early Holocene. Additionally, there is evidence for brief periods of coastline expansion over up to 20 km between 10,000 and 8,500 years BP during otherwise rapid flooding of the Dogger Bank.

The presented analysis of past sea level and geomorphological change of the Dogger Bank may provide context for better understanding of future landscape changes and sea level rise in formerly glaciated areas.

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